

GRO SOURCE CANDIDATES: (A) NEARBY MODEST-SIZE  
MOLECULAR CLOUDS, (B) PULSAR WITH WOLF-RAYET  
COMPANION THAT HAS LOST ITS H-ENVELOPE

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APPROX

ABSTRACT

Within 100 pc of the sun there are over a hundred cirrus clouds with masses of  $\sim 60 M_{\odot}$  and dense molecular cores with masses of  $\sim 4 M_{\odot}$ . If the local interstellar density of cosmic rays is also present in these clouds, the flux of  $\pi^0$ -decay gamma rays from the core of a cloud at a distance of 20 pc is  $\sim 3 \times 10^{-8}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . The flux from the more extensive cirrus cloud is  $\sim 4 \times 10^{-7}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ .

A relativistic beam of particles generated by a compact stellar object and incident upon a large, close companion can be a strong gamma-ray line source if more of the beam energy is used in interactions with C and O and heavier nuclei and less with H and He. This would be the case if the companion has lost its hydrogen envelope and nucleosynthesized much of its He into C, O and Ne. Such objects are Wolf-Rayet stars and it is believed that some Wolf-Rayet stars do, in fact, have compact companions. For a beam of protons of  $10^{37} \text{ erg s}^{-1}$ , the flux at 1 kpc of the 4.4 MeV  $^{12}\text{C}$  line could be as high as  $5 \times 10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . The fluxes of the deexcitation lines from the spallation products of  $^{16}\text{O}$  are also presented.

INTRODUCTION

The near-by cirrus clouds, although modest in size, are of particular interest. They are responsible for a substantial contribution to the nuclear spallation reactions of primary cosmic rays and thus to the secondary cosmic-ray nuclei observed near the earth. The bulk motion velocity of cosmic rays is estimated to be small; hence, the principal region of propagation of the local cosmic-rays (and probably also of the origin of many of the local cosmic rays) is largely within a few hundred parsecs. While more distant regions also contribute to the local cosmic rays (which also circulate in the Galactic halo), the contribution of the closer sources is likely to be more important. Gamma rays from the cirrus clouds thus are probes of nuclear reactions and pion production by cosmic rays and of the electron bremsstrahlung that take place in our Galactic neighborhood.

(NASA-CR-183491) GRO SOURCE CANDIDATES: (A)  
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Gamma-ray lines from stellar objects that have undergone advanced stages of nucleosynthesis and have unusual time- or evolution-dependent surface compositions are of special interest. Wolf-Rayet stars are such objects. Observations of gamma-ray lines from them would provide information on two items of interest: (1) The presence and energy spectrum of 10 - 100 MeV particles in pulsar or black-hole beams and (2) the Wolf-Rayet star composition which, while theoretical models exist, is still poorly known.

#### CIRRUS CLOUDS AND THEIR MOLECULAR CORES

Cirrus clouds in the solar system neighborhood have been explored by Turner, Rickard and Ping (1989). They report that over 100 cirrus clouds with a mean mass of about  $60 M_{\odot}$  are within 100 pc of the sun. These clouds have dense molecular cores with masses of  $\sim 4 M_{\odot}$ , densities of  $\sim 4 \times 10^4$  atoms  $\text{cm}^{-3}$ , and sizes of  $\sim 0.15$  pc. Molecules like  $\text{H}_2\text{CO}$ ,  $\text{C}_3\text{H}_2$  and  $\text{HC}_3\text{N}$  have been observed. Due to their close distance, many of these clouds are at high galactic latitude and were seen with IRAS.

The flux of gamma-rays from a cloud-core of mass  $4 M_{\odot}$  was calculated assuming that the density of cosmic rays in the cloud is the same as in local interstellar space. We use the formula given by Issa et al. (1981) for the flux,  $\phi$ :

$$\phi = 2.8 \times 10^{-12} M / d_k^2 \text{ photons cm}^{-2} \text{ s}^{-1}$$

where  $M$  is the cloud mass in units of  $M_{\odot}$  and  $d_k$  is the distance to the cloud in kpc. The flux at 20 pc (0.02 kpc) of gamma rays from the decay of  $\pi^0$  produced in a  $4 M_{\odot}$  core is then  $\sim 3 \times 10^{-8}$  photons  $\text{cm}^{-2} \text{ s}^{-1}$  and, from a  $60 M_{\odot}$  extended cirrus cloud, is  $\sim 4 \times 10^{-7}$  photons  $\text{cm}^{-2} \text{ s}^{-1}$ . Depending on the detector threshold, the gamma rays produced by electron bremsstrahlung could yield a similar flux from these sources.

In addition to the relatively small clouds within 100 pc, there are a few large clouds somewhat beyond 100 pc from which gamma rays have already been detected with COS-B. These clouds are probably also within the principal propagation region of the locally-observed cosmic rays. The distances and masses of these clouds and the observed gamma-ray fluxes are given by Issa et al. (1981) and are reproduced here. Possible reasons for the deviation of observed fluxes from expected values (such as enhanced cosmic-ray intensity in clouds or additional gamma-ray production by stars in clouds) are discussed by Issa et al. (1981).

	distance (pc)	mass ( $10^3 M_{\odot}$ )	flux ( $10^{-6}$ ph $\text{cm}^{-2} \text{ s}^{-1}$ )
$\rho$ Oph	160	6	1.1
Taurus	140	200	0.5
Cor. Aust.	150	100	0.4

## WOLF-RAYET STARS WITH BINARY COMPANIONS

Nuclear excitation and spallation lines have been observed from the sun. In particular, the flare of 27 April 1981 (discussed by Forrest 1983 and analysed for elemental abundances by Murphy et al. 1985a,b and for accelerated-particle anisotropies by Murphy et al. 1990) has shown what can be learned from gamma ray lines from astrophysical sources. We shall explore here whether such lines can be observed from typical galactic distances. Ramaty, Kozlovsky and Lingenfelter (1979) calculated the gamma-ray line intensities generated by cosmic-ray interactions with the galactic gas, adopting rather optimistic assumptions. Recent background estimates by Schonfelder, Ballmoos and Diehl (1987) and line intensity estimates by Higdon (1987) suggest that only the narrow-line emission of  $^{16}\text{O}$ , with an intensity of about  $2$  to  $8 \times 10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{rad}^{-1}$ , appears to be a promising candidate when a large, high-resolution detector is used. Morfill and Meyer (1981) explored gamma-ray line production from supernova remnants hidden in clouds. At 5 kpc, the fluxes of the 4.4 MeV  $^{12}\text{C}$  and 6.1 MeV  $^{16}\text{O}$  lines from such a remnant would be about  $6 \times 10^{-5}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ .

The observation of stellar excitation and spallation gamma-ray lines from galactic distances appears possible only with the combination of a powerful energy source for proton acceleration ( $10^{37}$  to  $10^{38}$  erg  $\text{s}^{-1}$ ), like a young pulsar or an accreting X-ray binary, and a target object consisting mainly of heavier nuclei (atomic numbers  $Z \geq 6$ ). The Wolf-Rayet stars are such objects. Many (about 1/3) of these are in binary systems with massive OB star companions that are about 2 to 3 times more massive than the Wolf-Rayet star (Vanbeveren 1987, Schulte-Ladbeck 1988). Abbott and Conti (1987) state in their review paper that there should also be Wolf-Rayet stars with collapsed (neutron-star or black-hole) companions. Some X-ray binary systems consisting of an O star and a collapsed companion could have the O-star evolve into a Wolf-Rayet star. In fact, Wolf-Rayet stars with periods of a few days (which would imply the presence of a compact companion) have been observed: the object HD 197406 is believed to be a Wolf-Rayet star with a black hole companion. A possible scenario could begin in a binary consisting of two massive stars. One enters the helium burning phase, expands to a red giant, transfers its hydrogen envelope to the companion, and becomes a Wolf-Rayet star with most of the mass of the system now in the OB companion. The Wolf-Rayet star becomes a supernova and, ultimately, a pulsar, while the OB companion expands to a giant star, loses its hydrogen envelope, and

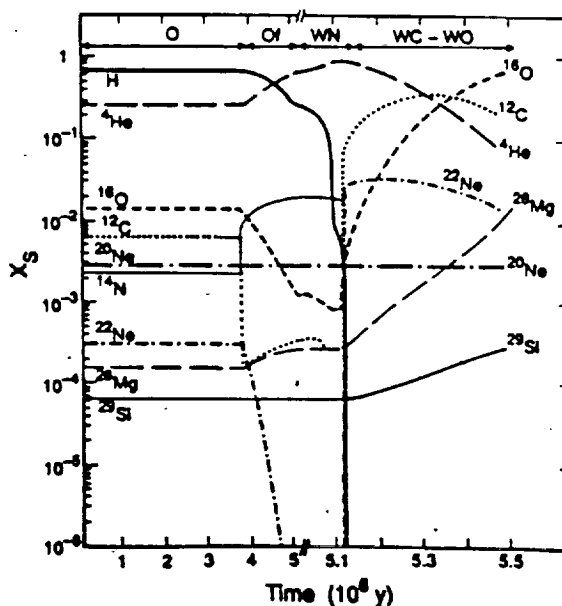


Figure 1. Wolf-Rayet star surface mass fractions (from Mewaldt 1989).

becomes a Wolf-Rayet star. (The pulsar may deflect the hydrogen envelope, or absorb it, becoming a black hole; a mass-accreting black hole can also generate a relativistic particle beam.)

The composition of Wolf-Rayet stars is not yet well known. In the C- and O-rich WC and WO stars, hydrogen has been depleted and  $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{22}\text{Ne}$ ,  $^{25}\text{Mg}$  and  $^{26}\text{Mg}$  have been formed as a result of helium burning and the  $\text{He} + ^{14}\text{N}$  reaction. The possible evolution of composition has been reviewed by Mewaldt (1989). We reproduce his Figure 14 (which is based on Prantzos et al. 1986) in Figure 1. A proton beam incident on a Wolf-Rayet star with such evolved composition is a much stronger gamma-ray line source than when the beam is incident on a star of solar composition (by a factor of  $\sim 100$ ). The beam energy is not wasted in proton-Hydrogen ionization losses and the relative abundance of the line-producing nuclei (C, O, etc.) are enhanced.

We have carried out calculations of gamma ray line fluxes using the Monte Carlo technique developed by Ramaty, Kozlovsky and Lingenfelter (1979) which incorporates laboratory measurements of the energy- and angle-dependent reaction cross sections and takes

into account Doppler shifts and relativistic beaming. The calculations were performed for thick-target interactions in which energetic protons produce the nuclear reactions while they slow down and stop in the ambient medium (e.g., see Ramaty and Murphy, 1987). Compton-scattering of the emerging photons was neglected. For the ambient composition, we use the abundances of Figure 1 at  $5.3 \times 10^6$  years. For the energetic proton number kinetic energy spectrum, we assume a power law with various values for the spectral index  $s$  and with low-energy cutoffs (due either to effects at the pulsar or to some helio-magnetic effect at the Wolf-Rayet star) of  $E_c = 25, 50, 100$  and  $200$  MeV. We assume a total beam power of  $10^{37}$  ergs  $\text{s}^{-1}$ . The calculations were made for energetic protons collimated into a beam with beam-to-observer angles ( $\theta_{\text{obs}}$ ) of  $0^\circ$ ,  $45^\circ$  and  $90^\circ$ . This angle is illustrated in Figure 2. For comparison, the fluxes from isotropic proton interactions have also been calculated. The fluxes given are the instantaneous values during the interaction time of the pulsar beam with the star. The flux value

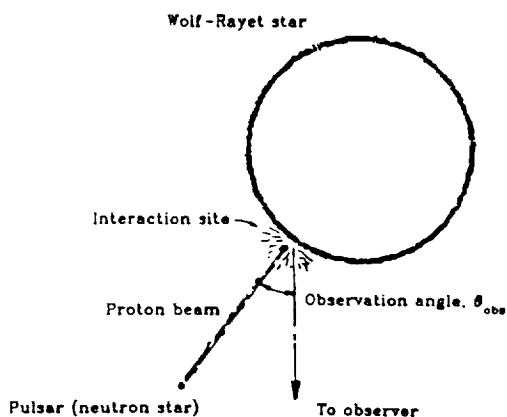


Figure 2. Binary geometry.

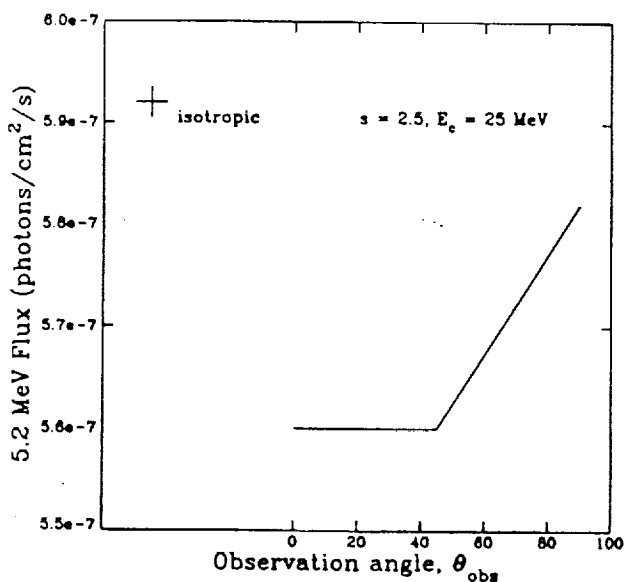


Figure 3. 5.2 MeV line-complex flux.

averaged over the rotation period of the pulsar would depend on the duty cycle of beam exposure. We focus on the 4.4 MeV line from  $^{12}\text{C}$  deexcitation and the  $\sim 5.2$  MeV line complex from deexcitation of  $^{14}\text{N}$ ,  $^{15}\text{N}$  and  $^{15}\text{O}$ .

Deexcitation line emission is quite isotropic regardless of the angular distribution of the accelerated particles. This is illustrated in Figure 3 where the  $\sim 5.2$  MeV flux for a beam of energetic protons with  $s = 2.5$  and  $E_c = 25$  MeV is plotted as a function of  $\theta_{\text{obs}}$  (together with the flux from an isotropic distribution). This weak ( $\sim 4\%$ ) dependence is due to the relativistic beaming of the photons emitted by the recoil excited nuclei. The cross sections for gamma-ray production generally exhibit a fairly sharp peak at an energy of  $\sim 10$ -30 MeV with the result that, in the thick-target limit, most of the interactions occur at these proton energies. The velocities of the recoil nuclei are therefore small and the beaming effect is correspondingly small.

The 4.4 MeV line flux is shown in Figure 4 for  $\theta_{\text{obs}} = 45^\circ$  as a function of the proton kinetic energy spectrum low-energy cutoff,  $E_c$ , for both  $s = 2.5$  and 3. The flux exhibits a significant sensitivity to  $E_c$ . This is also true of the  $\sim 5.2$  MeV flux. For the compositions and parameters considered here, the 4.4 MeV line flux could be as high as  $\sim 5 \times 10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . The 4.4 MeV line is produced primarily by direct excitation of ambient  $^{12}\text{C}$  nuclei, the contribution from  $^{16}\text{O}$  spallation being  $\sim 30\%$ . The  $\sim 5.2$  MeV line complex, however, is produced completely by spallation of  $^{16}\text{O}$  to  $^{14}\text{N}$ ,  $^{15}\text{N}$  and  $^{15}\text{O}$ . Since the cross sections for spallation reactions generally have higher energy thresholds and extend to higher energies than those for direct excitation, the ratio of the 4.4 MeV to  $\sim 5.2$  MeV fluxes is sensitive to the energetic proton kinetic energy spectrum in the  $\sim 10$ -100 MeV range where the cross sections are significant. This can be seen in Figure 5 where this ratio for  $E_c = 25$  MeV and  $\theta_{\text{obs}} = 45^\circ$  is plotted as a function of the power-law index. The ratio is also sensitive to the low energy cutoff, as can be seen in

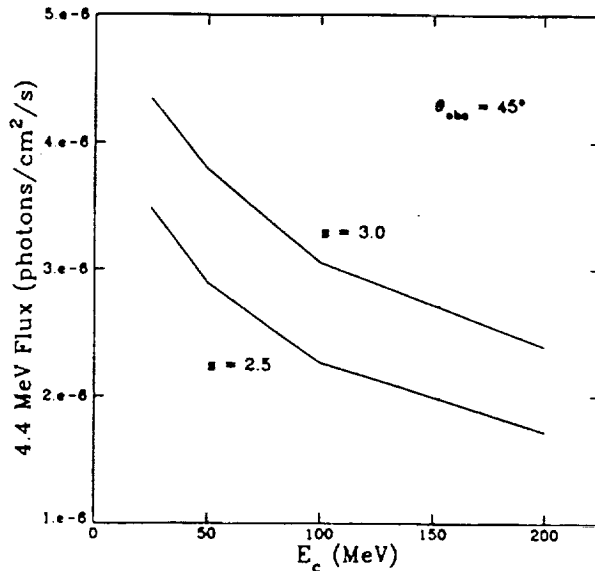


Figure 4. 4.4 MeV line flux.

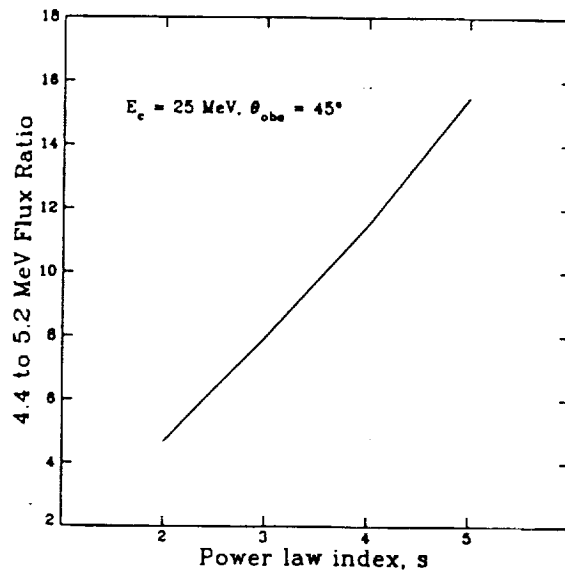


Figure 5. 4.4-to-5.2 MeV flux ratio.

Figure 6 where it is plotted as a function of  $E_c$  for  $s = 2.5$  and  $\theta_{\text{obs}} = 45^\circ$ . If theoretical considerations concerning the generation of the proton beam can constrain either  $s$  or  $E_c$ , then calculations such as these can be used to determine the other spectral parameter.

#### SUMMARY

We have calculated the gamma-ray flux expected from two possible sources: nearby, modest-sized molecular clouds and a pulsar-Wolf Rayet binary. Cosmic-ray interactions with the dense core of a molecular cloud at a distance of 20 pc could produce a flux of  $\pi^0$ -decay gamma rays of  $\sim 3 \times 10^{-8}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  if the local cosmic-ray intensity is present also in the clouds. The flux from the extended cloud could be  $\sim 4 \times 10^{-7}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ .

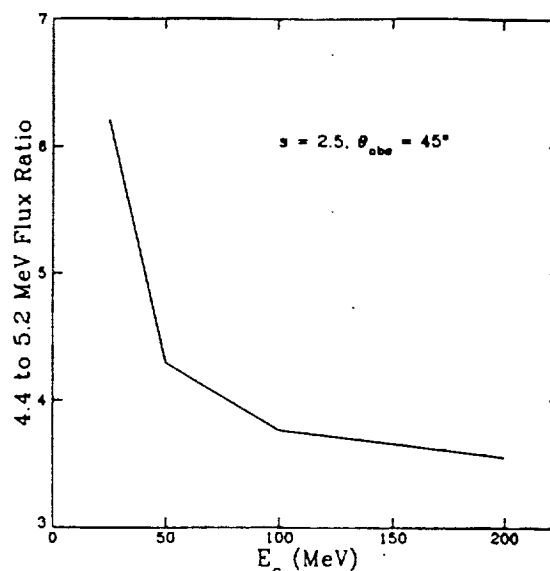


Figure 6. 4.4-to-5.2 MeV flux ratio.

A relativistic beam of particles generated by a compact stellar object and incident upon a large, close companion can be a strong gamma-ray line source if more of the beam energy is used in interactions with C and O and heavier nuclei and less in ionization losses with H and He. Wolf-Rayet stars have lost their hydrogen envelopes and have nucleosynthesized much of the He into C, O and Ne. Pulsar-Wolf-Rayet binaries are therefore good candidates for strong gamma-ray line production. We have calculated the fluxes in the 4.4 MeV  $^{12}\text{C}$  line and in the  $\sim 5.2$  MeV  $^{16}\text{O}$  spallation line complex resulting from interactions of a proton beam with a stellar atmosphere of typical Wolf-Rayet composition. We find that the 4.4 MeV line flux at 1 kpc could be as high as  $5 \times 10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ . In addition, the ratio of the 4.4 MeV flux to the  $\sim 5.2$  MeV flux is sensitive to the spectral shape of the energetic protons in the 10-100 MeV range. It could thus be used as a probe of pulsar acceleration mechanisms.

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